Status

- Focus has shifted to a neutrino factory
- Two comprehensive designs of acceleration (liancs, arcs)
  - Jefferson Lab, for Fermilab Study
  - CERN (Keil *et al.*)
- Jefferson Lab study
  - Low (2×10^{12}) charge per pulse
  - 200 MHz linac, RLA1; 400 MHz RLA2
  - Acceptance: 9.375 π mm transverse, 150 π mm longitudinal. 2.5σ
  - Accelerating off-crest
- CERN study
  - Higher charge per pulse
  - 350 MHz RLAs
  - Acceptance: 15 π mm transverse; emittance 17 mm longitudinal (3σ?)
  - Accelerating on-crest

Costs

- Based on Fermilab study
- Acceleration is 48% of cost, consumes 46% of average power
- Magnet lattices account for 7.9% of total cost
- Cavities, RF power, and their vacuum system account for 19.5% of total cost
- RLA1: 13% of total cost
- RLA2: 25% of total cost.
- Cost to 20 GeV:
  - Eliminate RLA2
  - Increase cost of RLA1 by 50%
    - Share factor of 2 in energy gain:
    - Longer linacs
    - More turns
  - Net result: 20% cost savings

Acceptances

- Fundamentally limited at initial linac
  - Longitudinal acceptance: about 250 π mm. Real estate gradient, frequency
    - Linacs longer (further off crest), but not too much
    - Energy acceptance of arcs must increase
    - Switchyard more difficult
  - Transverse acceptance: about 34 π mm. Tightly packed SC quadrupole doublet lattice.
    - More magnets
    - Increased aperture
    - Switchyard limitation?
  - Cost to do this:
    - Longer linacs: 5%; worse if forced to fewer turns
    - Magnetic lattice: 15% (triple acceptance, triple number of magnets and/or increase aperture)
- Cost benefits of reducing acceptance
  - Transverse: little; at most 4% to be had.
  - Longitudinal: increasing frequency, lower phase, or more turns: at most 10%

Beam Loading

- Two extremes to consider:
  - FNAL study: 2×10^{12} particles per pulse, 15 Hz
  - Palmer's scenario: 1.8×10^{13}, 2.5 Hz
- Leads to two limitations:
  - As extract more energy, energy gain for later turns too small to separate at switchyard. Limits number of turns.
  - Later bunches see different RF bucket.
    - Bunches placed regularly oscillate about different fixed point
      - Oscillates about correct energy
      - Displaced in time
      - More turns, smaller oscillation if fix synchrotron tune. Less energy loss before synchrotron oscillation corrects.
    - Given enough turns, filaments.
      - Average energy correct
      - Emittance blowup
    - If run isochronous, energy just drifts off
      - Greater energy offset
    - Primary limitation

- Results:
  - Low current (2×10^{12})
    - ⋆ Worst case: 800 MHz, 12–50 GeV, 4 turns
    - ⋆ Energy oscillation amplitude 154 MeV, where $\sigma_E = 341$ MeV
    - ⋆ 8% emittance blowup
    - ⋆ Improves with more turns
    - ⋆ Switching limitation: 15 turns
  - High current (1.8×10^{13})

$p_{\min}$ GeV/c	$p_{\max}$ GeV/c	f MHz	n	σ_E MeV	ΔE MeV	$\Delta\epsilon_L/\epsilon_L$ %
3	12	200	4	107	73	21
3	12	200	8	89	43	11
3	12	400	4	185	181	44
12	50	200	5	175	260	101
12	50	200	10	154	159	51
12	50	400	5	328	669	207

- ⋆ Large energy oscillations in RLA2
- ⋆ Can't go to higher frequency
- ⋆ Correction
  - ➢ Bunch/cool with one frequency, accelerate with slightly different frequency. Timing. Only correct average.
  - ➢ Higher rep rate. E.g., not all 6 AGS bunches at once. Increase average power. 6 bunches $\times$ 2.5 Hz = 15 Hz, same as FNAL study.

Higher Frequency Systems

- Example: RLA1 at 400 MHz, RLA2 at 800 MHz
- Motivation
  - Lower machine cost: as much as 10% of total
  - Reduce average power requirement: maybe 25% of total
- Difficulties
  - Low current: increased energy spread
    - Energy acceptance of arcs: 3.0% RMS in first arc of 400 MHz RLA1
    - Switchyards
  - High current: beam loading
    - Probably not possible

Research Items

- Handling higher currents
  - Clever compensation schemes (frequency offset)
  - Deliver proton driver bunches one at a time
- Larger energy acceptance arcs
  - Allow higher frequency operation
- Spreaders
  - Making more compact
  - Limitations in handling energy spread
  - Active kickers in RLA2???
  - Eliminate: single arc solutions
    - Need non-isochronous: beam loading
    - Need isochronous to get timing right
- Dogbone geometry
  - Will it save money?
    - Same arc count, half the linac, more loading.
      - Arcs longer (70% for 4 turns, more turns less)
      - More difficult arcs (low energy) get shorter
    - Or let arcs get shorter (30% for 4 turn racetrack, 4 pass dogbone), keep linac length.
    - Must separate horizontally then vertically
    - Tunnel/gallery a mess

- Beam loading, wakefields more complicated (end of trains sees front of train again)

- Existing designs
  - Very tight 2.5σ design
    - Cuts a lot of beam already
    - How much more will be cut when errors are in
    - How rigid is that 2.5σ?
  - Isochronous designs
    - Beam loading issue: need non-isochronous design to compensate
    - Longitudinal emittance blowup: factor of 2 in CERN design
    - Advantage: linacs shorter (cost issue), but only a few %